PATENT APPLICATION

COMPOUND LIGHT SOURCE EMPLOYING PASSIVE Q-SWITCHING AND NONLINEAR FREQUENCY CONVERSION

INVENTORS

Thomas J. Kane and Mark A. Arbore

FIELD OF THE INVENTION

The present invention relates generally to compound light sources employing lasers with passive Q-switches and nonlinear frequency converters to generate light in the desired wavelength range.

BACKGROUND OF THE INVENTION

Many applications require reliable, stable and efficient spectrally-pure high-power light sources. For example, projection display systems require light sources which exhibit these characteristics and deliver in excess of 1 Watt average power. These light sources should be inexpensive to produce and they need to generate output frequencies in the blue range and in the green range. For other applications light in the UV range is required.

The prior art teaches various types of light sources for generating light in the visible and UV ranges, including frequencies corresponding to blue and green light. A number

of these sources rely on a nonlinear frequency conversion operation such as second harmonic generation (SHG) to transform a frequency outside the visible range, e.g., in the IR range, to the desired visible or UV frequency. For example, U.S. Pat. No. 5,751,751 to Hargis et al. teaches the use of SHG to produce deep blue light. Specifically, Hargis et al. use a micro-laser which has a rare earth doped microlaser crystal and emits light at about 914 nm to drive SHG in a crystal of BBO producing output at about 457 nm.

U.S. Pat. No. 5,483,546 to Johnson et al. teaches a sensing system for high sensitivity spectroscopic measurements. This system uses a passively Q-switched laser emitting light at a first frequency. The light from the laser is transmitted through a fiber and converted to output light at a second frequency in the UV range. The conversion is performed by two frequency doubling crystals disposed far away from the Q-switched laser.

U.S. Pat. No. 6,185,236 to Eichenholz et al. teaches a self frequency doubled Nd:doped YCOB laser. The laser generates light of about 400 mW power at about 1060 nm and frequency doubles it with the aid of a frequency doubling oxyborate crystal to output light in the green range at about 530 nm. Eichenholz et al. combine the active gain medium and the frequency doubler in one single element to produce a compact and efficient light source.

In U.S. Pat. No. 5,909,306 Goldberg et al. teach a solid-state spectrally pure pulsed fiber amplifier laser system for

generating UV light. This system has a fiber amplifier in a resonant cavity and an acousto-optic or electro-optic modulator incorporated into the cavity for extracting high-peak-power, short-duration pulses from the cavity. These short pulses are then frequency converted in several non-linear frequency conversion crystals (frequency doubling crystals). The addition of the modulator into the cavity for extracting the pulses and placement of the fiber amplifier within the resonant cavity renders this system very stable and capable of delivering a spectrally-pure pulse. Unfortunately, this also makes the system too cumbersome and expensive for many practical applications such as display systems.

U.S. Pat. No. 5,740,190 to Moulton teaches a three-color coherent light system adapted for image display purposes. This system employs a laser source and a frequency doubling crystal to generate green light at 523.5 nm. Moulton's system also generates blue light at 455 nm and red light at 618 nm by relying on frequency doubling and the nonlinear process of optical parametric oscillation.

Unfortunately, the light sources described above and various other types of light sources taught by the prior art can not be employed to make stable, low-cost, efficient sources of light delivering 1 Watt of average power for display applications. This is in part due to the fact that frequency conversion, e.g., frequency doubling in crystals, is not a very efficient operation. If the frequency doubling crystal had extremely high non-linearity, then low power continuous wave (cw) lasers could be efficiently doubled to generate

output power levels near 1 Watt. However, in the absence of such frequency doubling crystals high-peak-power, short pulse lasers have to be used to obtain frequency doubled light at appreciable power levels. It should also be noted that providing such high-peak-power short pulses adds complexity to the design of the light sources and introduces additional costs.

U.S. Pat. No. 5,394,413 to Zayhowski addresses the issue of efficient frequency doubling by using a passively Q-switched picosecond microlaser to deliver the pulses of light. Such pulses can be efficiently converted, as further taught by Zayhowski in a frequency-doubling crystal. Devices built according to Zayhowski's teaching operate at relatively low average power levels and low repetition rates. Attempts to increase these parameters by pumping the microchip harder will cause multiple transverse-mode operation leading to degradation of beam quality and also incur increased pulse-to-pulse noise. Hence, Zayhowski's devices can not be used in applications such as projection displays, which require high average power and high repetition rates and good beam quality

Hence, what is needed is a stable and efficient source of light in the blue and green ranges which can be used in a projection display.

OBJECTS AND ADVANTAGES

It is therefore a primary object of the present invention to provide a stable, low-cost and efficient light source

generating light in the blue and green ranges at an average power output of 1 Watt or more.

It is another object of the invention to adapt such light source to image display systems, and in particular to scanned linear projection displays.

These and other objects and advantages of the invention will become apparent upon further reading of the specification.

SUMMARY

The objects and advantages are achieved by a light source employing a passively Q-switched laser for delivering a pulsed primary beam at a primary wavelength. The light source has a fiber amplifier for receiving the primary beam and amplifying it to produce a pulsed intermediate beam. The intermediate beam contains pulses at the primary wavelength. The Q-switched laser is configured such that these pulses have a certain format. Specifically, these pulses have a format corresponding to a certain frequency conversion efficiency, preferably higher than 10% or even higher than about 50%. The light source is further equipped with a nonlinear element for frequency converting the pulsed intermediate beam in a single pass at the conversion efficiency determined by the pulse format to produce a pulsed output beam at an output wavelength.

Depending on the application of the light source, the primary wavelength range can be chosen between 860 nm and 1100 nm and the output wavelength can range from 430 nm to 550 nm. This

output wavelength range covers blue and green wavelengths useful, e.g., in image displays.

In a preferred embodiment the fiber amplifier is a cladding-pumped amplifier. The core section and cladding section of the cladding pumped amplifier can be chosen to have suitable shapes and dimensions for efficient amplification of the primary beam. Furthermore, the length of cladding-pumped amplifier is preferably limited to less than 2 m.

The passively Q-switched laser is preferably equipped with a saturable absorber Q-switch. In order to generate intermediate pulses of appropriate format, i.e., above the nonlinear frequency conversion threshold, the Q-switch is set such that the pulsed primary beam has primary pulses with a duty cycle ranging from 0.01% to 1%. The Q-switch is also set such that the primary pulses have a certain pulse width and the interpulse separation between them is at least 100 times the pulse width. Furthermore, the Q-switch is also set to operate the passively Q-switched laser at a primary pulse repetition rate of at least 100 kHz.

The nonlinear element can be made up of one or more nonlinear optical crystals. For example, the nonlinear element can consist of one or more crystals from the borate family. Specifically, LBO or BBO crystals can be used as the nonlinear element.

In a preferred embodiment the light source of the invention is used in a display system. Once again, the light source is

equipped with the passively Q-switched laser for delivering the pulsed primary beam consisting of primary pulses at the primary wavelength and a fiber amplifier for receiving and amplifying the primary beam. The nonlinear element is positioned to receive the intermediate beam produced by the fiber amplifier and to frequency convert it in a single pass to produce the output beam at the output wavelength.

The display system has a plurality of display pixels for displaying a projected image. The display pixels are refreshed at a refresh rate. A synchronizing mechanism is provided for synchronizing output pulses of the pulsed output beam with the refresh rate. In a preferred embodiment, the synchronizing mechanism synchronizes the pulses with the refresh rate such that the output pulse rate is an integer multiple of the refresh rate.

As will be apparent to a person skilled in the art, the invention admits of a large number of embodiments and versions. The below detailed description and drawings serve to further elucidate the invention.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a diagram of a light source according to the invention.

Fig. 2 is a timing diagram illustrating pulse timing in the light source of Fig. 1.

Fig. 3A is a detailed cross sectional view of a particular Q-switched laser suitable for use in a light source according to the invention.

Fig. 3B is a diagram of another Q-switched laser suitable for use in a light source according to the invention.

Fig. 4A&B are cross sectional views of fiber amplifiers suitable for use in a light source of the invention.

Fig. 5 is a diagram of another embodiment of a light source according to the invention.

Fig. 6 is an isometric view of a display system in accordance with the invention.

Fig. 7 is a plan view of a pixel in the display system of Fig. 6.

Fig. 8 is a timing diagram illustrating the synchronization of the refresh rate with the pulse rate.

DETAILED DESCRIPTION

Although the following detailed description contains many specific details for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the exemplary embodiments of the invention described below are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

Fig. 1 illustrates a light source **10** with a passively Q-switched laser **12** and a fiber amplifier **14** according to the invention. Light source **10** has a pump source **16** for producing pump light **20**. In this embodiment, pump source **16** is a laser equipped with a wavelength tuning mechanism **18**. Laser **16** is designed to deliver pump light **20** in the form of a continuous wave (cw) light beam. Many types of lasers are suitable for use as pump source **16**. For example, diode lasers emitting pump light **20** within the 750 nm to 1100 nm range can be used. The power level of these diode lasers can be between 100 mW and 4000 mW.

~~A lens **22** is provided before pump source **16** for focusing pump light **20** and directing it to an input coupler **24** of Q-switched laser **12**. Input coupler **24** is designed to admit pump light **20** into a cavity **26** of passively Q-switched laser **12**. Cavity **26** has a length L defined between input coupler **24** and an output coupler **28**. Although in the present embodiment cavity **26** is linear and couplers **24**, **28** are in the form of mirrors, a person skilled in the art will appreciate that other types of cavities and coupling elements can be used.~~

Cavity **26** contains a gain medium **30**. Gain medium **30** exhibits a high amount of gain per unit length when pumped with pump light **20**. Typically, high gain is achieved by providing a high doping level in gain medium **30** within the cross section traversed by light **20**. Doped materials with suitable amounts of gain to be used as gain medium **30** include Yb:YAG at the 1030 nm and 980 nm transitions, Nd:Vanadate at the 880 nm, 914 nm, and 1064 nm transitions and Nd:YAG at the 946 nm and 1064 nm transitions. A person skilled in the art will be familiar with other suitable materials and the corresponding transitions. Some of these materials include Yb Glass Fiber (980 nm transition), Yb Glass Fiber (1020-1120 nm transition), Nd Glass Fiber (880-940 nm transition), and Nd Glass Fiber (1050-1090 nm transition).

Cavity **26** also contains a passive variable loss element or passive Q-switch **32**. Preferably, passive Q-switch **32** is a saturable absorber Q-switch such as chromium:YAG, which functions in the wavelength range from 860 nm to 1100 nm. Alternatively, semiconductors or semiconductor material structured to act as a mirror can be used as passive Q-switch **32**. Passive Q-switch **32** is adjusted for switching on and off such that, when subjected to cw pumping by pump light **20**, passively Q-switched laser **12** generates a pulsed primary beam

34 at a primary wavelength λ_p. For clarity, only a single primary pulse **36** of primary beam **34** exiting cavity **26** through output coupler **28** is indicated in Fig. 1. Primary wavelength λ_p corresponds to the selected transition of gain medium **30**. This transition can be selected in any suitable range. In the present case, the transitions are selected in a wavelength range between 860 nm and 1100 nm.

Light source **10** also has a pump source **38** for supplying a pump light **40**. Source **38** can be a diode laser operating in the wavelength range from 750 to 1000 nm and delivering between 1 and 100 Watts of power. Preferably, source **38** is fiber coupled laser such as a LIMO type laser (available from LIMO Laser Systems, laser@limo.de). A lens **42** and a beam combiner **44** are positioned in the path of pump light **40**. Lens **42** focuses pump light **40** such that it is in-coupled into fiber amplifier **14**. In particular, with the aid of lens **42** pump light **40** is in-coupled into a cladding **46** of fiber amplifier **14**. A lens **48** is also positioned in the path of primary beam **34** before beam combiner **44**. Lens **48** focuses primary beam **34** such that after being combined with pump light **40** by beam combiner **44**, primary beam **34** is in-coupled into a core **50** of fiber amplifier **14**.

Fiber amplifier **14** produces a pulsed intermediate beam **52** at primary wavelength λ_p from primary beam **34**. Preferably, pulsed intermediate beam **52** exhibits high peak power, e.g., in the range of 10,000 Watts in each pulse **54** (only one pulse shown for reasons of clarity). To achieve such high peak power fiber amplifier **14** has a short length D, e.g., D is on the order of 2 meters, so as to suppress stimulated Raman scattering (SRS). In addition, to achieve efficient absorption of pump light **40** in core **50** over such short length D, cladding **46** is preferably small, e.g., between 100 µm and 200 µm in diameter. Furthermore, core **50** is preferably large,

e.g., between 5 μm and 10 μm diameter, and exhibits a high doping level, e.g., 0.5% or more. A person skilled in the art will be able to select the appropriate dopant for doping core **50** to amplify primary beam **34** based on primary wavelength λ_p. Suitable doping ions when primary wavelength λ_p is in the green range are Ytterbium ions while Neodymium ions can be used for amplifying primary beam **34** when its light is in the green or blue range.

A lens **56** and a beam guiding element **58**, in this case a mirror, are positioned in the path of pulsed intermediate beam **52**. Lens **56** shapes pulsed intermediate beam **52** and element **58** deflects it such that beam **52** is in-coupled into a nonlinear element **60**. Nonlinear element **60** is selected for its ability to frequency convert pulses **54** of pulsed intermediate beam **52** in a single pass to produce a pulsed output beam **62** at an output wavelength λ_{out}. Only one pulse **64** of output beam **62** is illustrated for clarity.

In the present embodiment, nonlinear element **60** consists of a single nonlinear optical crystal capable of converting primary wavelength λ_p to output wavelength λ_{out} in the UV, green or blue range. The conversion process is second harmonic generation (SHG) and is well-known in the art. SHG doubles the frequency of intermediate beam **52**, or, equivalently, halves primary wavelength λ_p such that $2\lambda_{out}=\lambda_p$. Hence, when primary wavelength λ_p is in the range from 860 nm to 1100 nm output wavelength λ_{out} will be in the range from 430 nm to 550 nm.

Preferably, optical crystal used as nonlinear element **60** is a borate crystal. In fact, preferably optical crystal is an LBO or BBO crystal. Also, although only one crystal is employed as nonlinear element **60** in the present embodiment, several can be used, as will be appreciated by those skilled in the art. In addition, any appropriate phase matching technique known in

the art is employed to ensure efficient SHG in nonlinear element **60**.

During operation, pump source **16** is tuned by mechanism **18** to generate pump light **20** in the form of a cw beam at the requisite wavelength to pump gain medium **30**. Passively Q-switched laser **12** is adjusted such that primary pulses **36** of output beam **34** are controlled. To achieve this, one notes that a round-trip time, t_{rt}, of cavity **26** is related to length L of cavity **26** by the equation:

$$t_{rt} = \frac{2L}{c},$$

where c is the speed of light. Hence, round-trip time t_{rt} can be set by selecting length L of cavity **26**. Meanwhile, passive Q-switch **32**, in this case saturable absorber Q-switch is adjusted by setting its inter-pulse time. This is done by choosing the appropriate saturable loss, q_o, of the absorbing material and using the fact that the repetition rate of passive Q-switch **32** is proportional to pump power or the power level of pump light **20**, and that increasing the repetition rate produces longer primary pulses **36**. A person skilled in the art will know how to adjust these parameters to obtain the appropriate inter-pulse time and will also find additional teachings provided by G.J. Spühler et al., "Experimentally Confirmed Design Guidelines for Passively Q-Switched Microchip Lasers Using Semiconductor Saturable Absorbers", J. Opt. Soc. Am. B, Vol. 16, No. 3, March 1999, pp. 376-388 and other sources.

In a preferred embodiment, length L is very short, e.g., L is on the order of 10 millimeters or less. Preferably, L is even less than 1 millimeter. The inter-pulse time of passive Q-switch **32** is selected such that primary pulses **36** have a pulse

duration t_p of about 100 times round-trip time t_{rt} as illustrated in Fig. 2. In addition, passive Q-switch **32** is also set such that the time between successive primary pulses **36** at times t_i and t_{i+1} defining an interpulse separation is at least 100 times pulse time t_p and preferably up to 10,000 times pulse time t_p. Thus, in the preferred embodiment, primary pulses **36** have a duty cycle ranging from .01% to 1%.

Primary pulses **36** exiting passively Q-switched laser **12** should preferably have a peak power level of at least 10 Watts and preferably between 50 and 500 Watts. When primary pulses **36** enter fiber amplifier **14**, which has a gain of about 100 or more (e.g., between 50 and 500) they are amplified to form intermediate pulses **54** with over 1,000 Watts and preferably over 10,000 Watts of peak power while preserving primary pulse timing as described above. At this power level and timing, intermediate pulses **54** have a pulse format which is above a nominal nonlinear frequency conversion threshold for SHG in nonlinear element **60**. Specifically, for the purposes of this description, nominal nonlinear frequency conversion threshold is defined to correspond to a pulse conversion efficiency of at least 10%. Preferably, the conversion efficiency is close to 50% or even higher. Now, at 10,000 Watts of peak power intermediate pulses **54** exhibit approximately 50% efficient conversion to output pulses **64** in LBO or BBO crystals of 20 mm length.

By operating light source **10** as described above it is possible to obtain output beam **62** with output pulses **64** in the wavelength range from 430 nm to 550 nm at up to 5,000 Watts of peak power with a duty cycle between .01% and 1%. The actual application for which light source **10** is used will determine the exact peak power requirements for output pulses **64** and the required output wavelength λ_{out}.

Light source **10** is a compound source with a number of elements requiring proper alignment and positioning. Several components of light source **10** can be simplified to reduce the complexity and cost of light source **10**. Fig. 3A illustrates a preferred embodiment of a passively Q-switched laser **80** for light source **10**. Laser **80** consists of a thin plate of saturable absorber **82** serving as the passive Q-switch and of a thin plate of gain medium **84**. Saturable absorber **82** is bonded or otherwise attached to gain medium **84**. It is also possible to align the plates of saturable absorber **82** and gain medium **84** in parallel and in close proximity. In this event the facing surfaces of the plates should be coated for low reflection.

A first mirror **86** and a second mirror **88** are deposited directly on the external surfaces of the plates of saturable absorber **82** and gain medium **84**. First mirror **86** is an input coupler and admits pump light **20** into laser **80**. Second mirror **88** is an output coupler, and serves for coupling out primary pulses **36** of pulsed primary beam **34**. Mirrors **86** and **88** define a resonant cavity **90** of length L, which is short, e.g., on the order of 1 mm or less. Laser **80** is sometimes referred to as a microchip laser in the art. For further information on design guidelines for microchip lasers the reader is again referred to G.J. Spühler et al., "Experimentally Confirmed Design Guidelines for Passively Q-Switched Microchip Lasers Using Semiconductor Saturable Absorbers", J. Opt. Soc. Am. B, Vol. 16, No. 3, March 1999, pp. 376-388.

Fig. 3B illustrates another embodiment of a passively Q-switched laser **100** for light source **10**. Laser **100** has a gain fiber **102** disposed in a resonant cavity **104**. Resonant cavity **104** is defined between a mirror **106** for in-coupling pump light **20** and a mirror **108** for out-coupling pump beam **34**. Although cavity **104** is defined by mirrors **106**, **108** in this case,

gratings or coatings placed near the end of gain fiber **102** could also be used to define cavity **104**. In fact, sometimes only one grating or coating can be used and the other end of gain fiber **102** can be cleaved to obtain Fresnel reflection from the cleaved surface. A person skilled in the art will appreciate how to process gain fiber **102** to establish cavity **104**.

Gain fiber **102** is doped with gain material, as is known in the art. A saturable loss absorber **110** serving as passive Q-switch is spliced with gain fiber **102**. Alternatively, saturable loss absorber **110** can be a segment of fiber doped with the saturable absorber material or it can even be a separate segment of fiber placed between the end of gain fiber **102** and mirror **108**.

Fig. 4A illustrates in cross section a fiber amplifier **120** which can be used by light source **10**. Fiber amplifier **120** has an active, circular core **122** surrounded by a cladding **124** with an irregular cross section. A protective outer cladding **126** surrounds cladding **124**. Pump light **40** is in-coupled into cladding **124**, while primary beam **34** is in-coupled into core **122**, as described above. Because of the irregular cross section of cladding **124**, pump light **40** is more efficiently delivered to core **122** for amplifying primary beam **34**. Thus, the length of fiber amplifier **120** can be kept short, e.g., 2 meters or less, as indicated above.

Fig. 4B illustrates yet another fiber amplifier **130** which can be used by light source **10**. Fiber amplifier **130** has an active, circular core **132** surrounded by a first cladding **134**. Cladding **134** has a circular cross section and is in turn surrounded by a second cladding **136** with an irregular cross section. Fiber amplifier **130** has a protective outer cladding **138**. The addition of cladding **134** and adjustment of its index

of refraction makes it possible for fiber amplifier **130** to alter the propagation characteristics of fiber amplifier **130** to improve the in-coupling of pump light **40** into core **132** and to improve the amplification efficiency. Once again, this enables one to keep the length of fiber amplifier **130** short. A person skilled in the art will recognize that the appropriate choice of fiber amplifier, its cross section, its length as well as pulse time t_p and pulse energy are required to avoid fiber optic nonlinearities and especially those associated with stimulated Raman scattering as well as stimulated Brillouin scattering (SBS) and self phase modulation.

Fig. 5 is a diagram of another embodiment of a light source **140** according to the invention. A primary beam generator **142** combines a pump source and a passively Q-switched laser and delivers a primary beam **144**. Primary beam **144** consists of pulses **146** (only one indicated) of light at primary wavelength λ_p. Pulses **146** are formatted in accordance with the guidelines given above.

Primary beam **144** is delivered to a fiber amplifier **148**. Fiber amplifier **148** amplifies primary beam **144** to produce an intermediate beam **150** still at primary wavelength λ_p. Intermediate beam **150** consists of pulses **152** (only one shown) which have a pulse duration, an inter-pulse separation and peak power defining a format calibrated to obtain at least 10% frequency conversion efficiency and preferably up to 50% or higher frequency conversion efficiency in a nonlinear element **158**.

A lens **154** and a beam guiding element **156** are placed in the path of intermediate beam **150** for directing it to nonlinear element **158**. Nonlinear element **158** has a waveguide **160** with a quasi-phase-matching (QPM) grating **162** disposed therein. QPM

grating **162** is designed for phasematching the frequency conversion operation by which intermediate beam **150** is converted to an output beam **164** at output wavelength λ_{out}. The frequency conversion operation producing output beam **164** is second harmonic generation (SHG). Conveniently, nonlinear element **158** with QPM grating **162** is a PPLN, PPLT, PPKTP, MgO:LN or other poled structure.

Alternatively, the frequency conversion operation can be optical parametric generation (OPG) or another type of nonlinear frequency conversion operation such as difference frequency generation (DFG). OPG is an alternative to SHG because it is a highly-efficient, single-pass and single input wavelength process (the requisite idler and signal beams are usually obtained by vacuum amplification). In addition, the output spectrum of output beam **164** is somewhat broadened (typically by a few nm) when OPG is used, making it more suitable for certain applications, e.g., for image displays. On the other hand, when DFG is used as the frequency conversion operation a beam **166** at wavelength λ_1 is required to mix with intermediate beam **150** in nonlinear element **158**. In such situations pulses **168** (only one shown) of beam **166** should be synchronized with intermediate pulses **152**. Also, beam guiding element **156** is then adapted to function as a beam combiner. Furthermore, a filter **170** can be provided for removing unwanted frequencies exiting nonlinear element **158**.

Several frequency conversion processes, i.e., a cascaded nonlinear conversion process can be implemented in nonlinear element **158** and use beam **150** in conjunction with beam **166** (and/or other beams besides beam **166**) or without it. Such operations may involve several nonlinear operations in series. For example, second harmonic generation followed by sum frequency generation, resulting in third harmonic generation.

In a particularly convenient embodiment of the invention shown in Fig. 6 an image display system **200** employs a projection light source **202**. In this case image display system **200** is a scanned linear image display system. Projection light source **202** has a first and a second light source (not shown in this figure) as described above for producing output in the green wavelength range and in the blue wavelength range, respectively. These two light sources are used one after the other or sequentially for a certain amount of time, as described below. Each of these two light sources is set to deliver an output beam **206** at an average power of 2.5 Watts. For this purpose the duty cycle of the intermediate beam is set at .05% and the peak power of intermediate pulses is set at 10,000 Watts. With this pulse format the conversion efficiency is about 50%. Hence, output beam **206** will have an average power of 2.5 Watts (5,000 Watts of peak power at .05% duty cycle).

It is convenient to also provide projection light source **202** with a third light source producing output in the red wavelength range. In this embodiment, the third light source is a diode laser producing 2.5 Watts average power at a red wavelength. The output of the third light source is coordinated with the output of the first and second sources, such that only one color is present in output beam **206** at a time.

Image projection system **200** has cylindrical beam shaping and guiding optics **208**, generally indicated by a cylindrical lens. Of course, guiding optics **208** will typically include a number of lenses and other elements, as will be appreciated by a person skilled in the art. Optics **208** are adapted for line-wise image scanning by expanding output beam **206** along the vertical direction.

An image generator **216** having a vertical line **218** of pixels p_i is positioned in the path of expanded output beam **206**. Image generator **216** can be any suitable unit capable of generating images line-by-line and requiring illumination by red, green and blue wavelengths in succession, as provided in output beam **206**. In the present embodiment image generator **216** is a grating light valve array made up of vertical line **218** of independently controlled grating-type light valves **220**. Each one of light valves **220** corresponds to a pixel. Fig. 7 illustrates a light valve **220A** having adjustable grating strips **222A**. Strips **222A** are moved by a suitable mechanism to adjust the grating of light valve **220A** to diffract a particular color into a projection beam **228**. The principles of operation and design of grating-type light valves are known and the reader is referred for further information to David T. Amm et al., "Optical Performance of the Grating Light Valve Technology", presented at Photonics West - Electronic Imaging 1999, Projection Displays.

A linear scanner **210** having a rotating deflection unit **212** and a control **214** is provided for line-wise scanning of projection beam **228**. The scanning speed is controlled by control unit **214** which adjusts the angular speed of rotation ω of deflecting unit **212**. A person skilled in the art will recognize that other types of optics and scanning devices can be used, depending on the method of image scanning.

The scanned image produced by image generator **216** is projected on a display screen **224** with the aid of optics **226**, generally indicated by a lens. In particular, light valves **220**, are set to diffract red, green and blue wavelengths provided in beam **206** to generate an image linewise in the diffracted projection beam **228**. Beam **228** is projected by optics **226** on screen **224** to display the image to a viewer. In one implementation certain light valves **220** are dedicated to each color.

Preferably, in this case valves **220** are subdivided into groups of three one for diffracting blue, another for diffracting green and a third one for diffracting red into projection beam **228**. Alternatively, light valves **220** can be modulated to diffract different colors at different times (e.g., by time-multiplexing).

A synchronizing mechanism **230** is connected to projection light source **202** and to control **214** of linear scanner **210**. Mechanism **230** is provided to coordinate the timing of output pulses **232** in output beam **206** with the line scanning performed by linear scanner **210**.

When operating image display system **200** projection light source **202** is set to deliver output pulses **232** at the green wavelength from light source one, at the blue wavelength from light source two, and at the red wavelength from light source three. The pulses are repeated at a certain rate (i.e., at the inter-pulse rate set as described above). Specifically, as better illustrated in Fig. 7, light source **202** is set to deliver a number q of pulses **232** during a refresh time $t_{refr.}$ which is the time allotted by control **214** of linear scanner **210** to generating each line of the image. Preferably, the number of pulses **232** during refresh time $t_{refr.}$ should be an integer multiple of the refresh rate, e.g., 6 or more pulses **232** per refresh time $t_{refr.}$ (i.e., q=6). For better visualization, Fig. 8 illustrates the q pulses **232** delivered by projection light source **202** during each refresh time $t_{refr.}$.

The number q is dictated by the angular velocity ω of rotating deflection unit **212**. Synchronizing mechanism **230** adjusts the timing of output pulses **232** in coordination with angular velocity ω of unit **212** such that number q of pulses **232** delivered during each refresh time $t_{refr.}$ is equal. Refresh time $t_{refr.}$ is dictated, among other, by the perception

parameters of the human eye. Pixels p_i in each line **218** have to be refreshed rapidly enough for the human eye not to notice any appreciable image discontinuities. This condition determines the length of refresh time $t_{refr.}$ given the number of lines of which the scanned image is composed.

In display systems with a large number of lines, e.g., on the order of 1,000 to 2,000 the appropriate refresh rate requires that passively Q-switched laser for the first and second light sources (green and blue) be set at a primary pulse repetition rate of at least 100 kHz.

The light source of the invention can also be used in image displays which are not scanned line-by-line but employ some different scanning procedure. It can also be used in display systems using as image generating pixels liquid crystals or micro-mirror arrays. In still another embodiment, the light source of invention can be used to illuminate a two-dimensional array of pixels generating an image in a non-scanned image display system. A person skilled in the art will appreciate that various multiplexing and scanning methods can be employed to operate such scanned and non-scanned display systems. Additionally, a person skilled in the art will recognize that the applications of the light source in a display system is only one of the many applications for this light source can be used.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alterations can be made herein without departing from the principle and the scope of the invention. Accordingly, the scope of the present invention should be determined by the following claims and their legal equivalents.